ARMY RESEARCH LABORATORY

Benchmark Tests and Analyses for Ordnance Fragmentation and Propagation Models

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Abstract

Two models were developed at the U.S. Army Research Laboratory to enhance predictive techniques for propagation between ammunition stacks. For a mass-detonating ammunition stack, the FragProp model predicts probabilities of reaction in the energetic components of neighboring stacks by means of primary fragments as a function of distance between the stacks. An adjunct model, FragGen, was developed to estimate primary fragments from thin-walled warheads and detonable rocket motors. In order to increase confidence in the predictions from these models, benchmark tests were conducted. These include propagation tests with pallets of 155-mm M107 projectiles and arena fragmentation tests with Hellfire missiles and 155-mm M864 ICM projectiles. The test results are analyzed and compared with predictions from the models.

Acknowledgments

The authors are grateful to Carl Halsey, Jack Brown, and their coworkers at the Naval Air Warfare Center, China Lake, CA, for completion of the tests; to Robert Rossi and Duane Scarborough at the Defense Ammunition Logistics Activity, Picatinny Arsenal, NJ, for funding this effort; and to Robert Frey and Lawrence Vande Kieft for many helpful technical discussions.

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Table of Contents

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List of Figures

List of Tables

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1. Background

The Munitions Survivability Technology program was initiated by the Army's Defense Ammunition Logistics Activity, Picatinny Arsenal, NJ, in order to develop a rapidly deployable system of fragment barricades combined with lightweight fire-inhibiting blankets, along with guidelines for their use to prevent propagation of explosions and fire between stacks of Army munitions. One of the program's objectives is to enhance predictive techniques for propagation of detonation and burning between ammunition stacks. The primary predictive tool available is the FragProp model developed at the U.S. Army Research Laboratory. FragProp predicts probabilities of propagation between ammunition stacks by means of fragmentation. In order to represent a source or donor stack, the model requires arena test data characterizing the fragment output from the ammunition item comprising the stack. To account for effects of interactions between fragments from nearly simultaneously detonating adjacent munitions, more than one item must be included in the arena test source. In general, such data are only available for some of the munitions that derive their effectiveness from fragmentation. Items such as shaped-charge missile warheads and detonable rocket motors, which may also produce hazardous fragments, have not been experimentally characterized, and an adjunct model, FragGen, was developed to estimate their primary fragment output. In order to establish confidence in the predictions from these models, benchmark experiments for propagation and fragment output (arena tests) were conducted. Additionally, although data characterizing fragment output from submunitions may exist, no data or predictive techniques are available to characterize fragments produced when these are detonated en masse in their carriers. Tests were also conducted in an attempt to provide this information

2. Brief Review of FragProp

FragProp (Starkenberg, Benjamin, and Frey 1996) is based on an earlier computer program, FragHaz (McClesky 1988), that was developed to predict the hazard to a human target due to fragmentation from an exploding ammunition stack. FragProp is designed to predict

probabilities of detonation and burning propagation between two ammunition stacks as functions of the distance between them. The donor stack description and Monte-Carlo analysis of the trajectories of the fragments characterizing that stack are nearly identical to those used in FragHaz. Effects of penetrating external containers and user-specified limits on fragment mass and initial elevation angle were added. FragProp includes descriptions of the vulnerable components (i.e., warheads and rocket motors) of munitions in the acceptor stack and applies detonation initiation and burning ignition criteria whenever a fragment impacts the target stack. The effects of penetrating external containers are included here also. The vulnerability of a weapon component to initiation of detonation by fragment impact is described by the Jacobs-Roslund formula for critical impact velocity (Liddiard and Roslund 1993). The model for ignition of burning makes use of a threshold corresponding to a specified residual velocity computed using the THOR equations. The burning produced may be either mild or violent. The violence of the burning response is not predicted by FragProp. Analysis has shown that a residual velocity of zero can be used as a worst-case without inordinately increasing the distance associated with a given probability.

3. Fragment Propagation Tests

3.1 Choice of Ammunition. The objective of the fragment propagation tests was to determine the frequency with which a well-characterized detonating donor stack produces detonation in nearby well-characterized acceptor stacks for comparison with FragProp predictions. Since applicable fragmentation data for 155-mm M107 projectiles filled with Composition B are available, along with Jacobs-Roslund constants for initiating Composition B and THOR equation constants for penetration of mild steel, pallets of these projectiles were selected for propagation tests. Each pallet holds eight projectiles, and each projectile contains 15.4 lb of Composition B. The distance between projectiles in the pallets is approximately 7/8 in. The item is classified in hazard division 1.1D for storage and shipping. Hawthorne Army Ammunition Plant, NV, supplied 144 projectiles for use in three tests.

3.2 Propagation Test Arrangement. Three tests were conducted at the Naval Air Warfare Center, China Lake, CA, in the center of a flat dry lakebed approximately one-half mile wide. A schematic of the test arrangement is shown in Figure 1,and a photograph is shown in Figure 2. In each test, the donor was configured by placing two eight-projectile pallets of M107s side by side, producing a stack having four projectiles on each of its four faces (identified as north, east, south, and west). A photograph of the donor pallets is shown in Figure 3. One acceptor stack, consisting of a single M107 pallet, was placed opposite each of the donor faces at a standoff distance determined with reference to results of a FragProp analysis. The same standoff distance was used for all four acceptors. In order to prevent acceptor-to-acceptor interactions, two steel barriers were set up next to each acceptor pallet on the lines of sight to the adjacent acceptor pallets, without interfering with the line of sight to the donor pallets. The relationship between the donor, one of the acceptors, and the barriers is shown in Figure 4. In the second and third tests, steel witness plates, 1/2 in thick, were placed under the acceptors to indicate the severity of reaction. High-speed cameras were set up 1,200 ft from the donor at 65 and 110° from north. Each of the four center projectiles in the donor was boosted with approximately 1.7 oz of Composition C-4, and each booster was primed with 24 in of 50-gr/ft detonating cord. The detonating-cord connections were cut to the same length to ensure simultaneous initiation of the projectiles. The initiating device was a Reynolds exploding bridgewire detonator (RP-83). After each test, most of the fragments and all of the unexploded projectiles were collected for evaluation.

3.3 FragProp Predictions. An analysis of the test configuration was conducted using FragProp. In previous analyses, Jacobs-Roslund constants for flat-tipped projectiles had been used as a worst case. In the present analysis, these were replaced with constants for hemispherical-tipped projectiles, which require higher velocities to initiate explosives, and are considered more representative of the actual fragments produced by the M107 projectiles. The results of this analysis are summarized in Table 1. Probabilities of propagation of detonation and burning at stack-to-stack standoff distances of 55, 39, and 28 ft are given.

Table 1. Results of FragProp Analyses

Standoff (ft)	55	39	28
Detonation Probability (%)	25	50	75
Burning Probability (%)	29	55	80

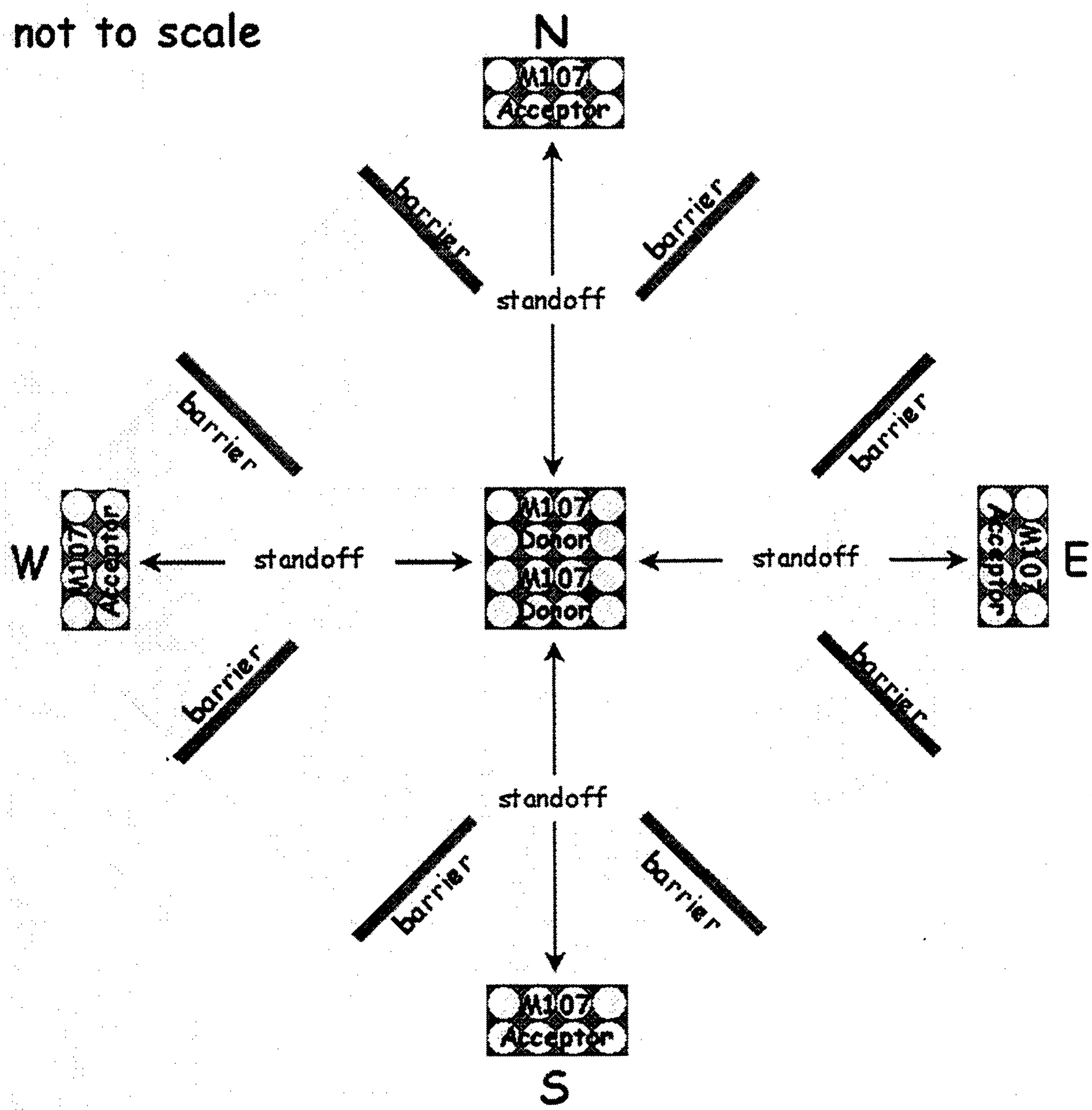


Figure 1. Schematic of the Fragmentation Propagation Test Arrangement.

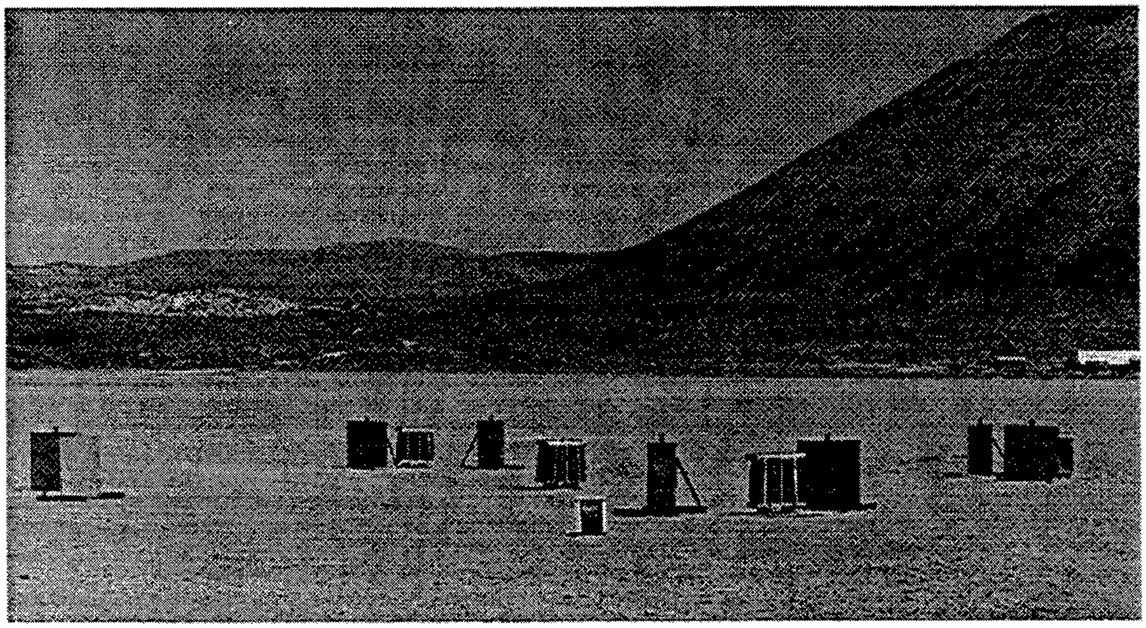


Figure 2. View of the Fragmentation Propagation Test Arrangement.

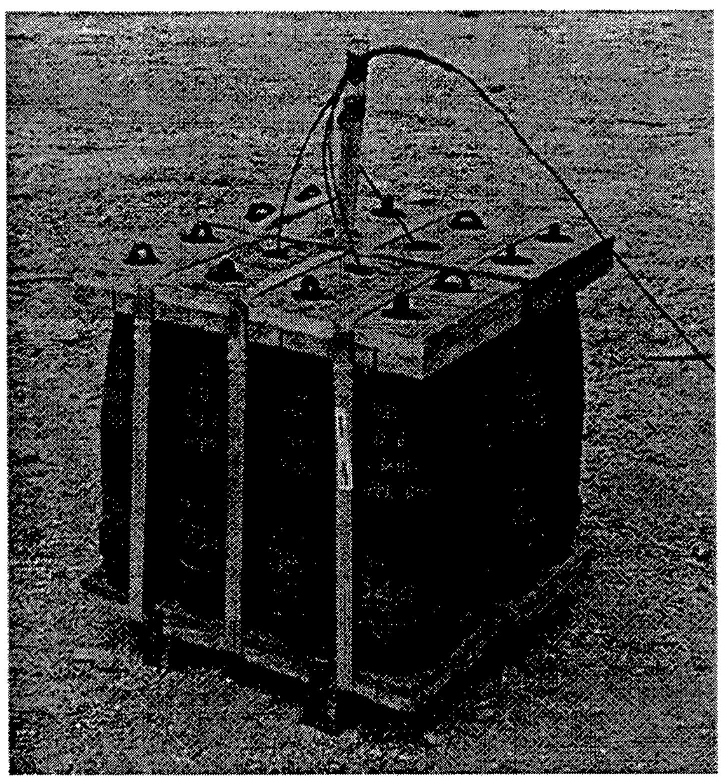


Figure 3. A Primed Donor Stack Consisting of Two M107 Pallets.

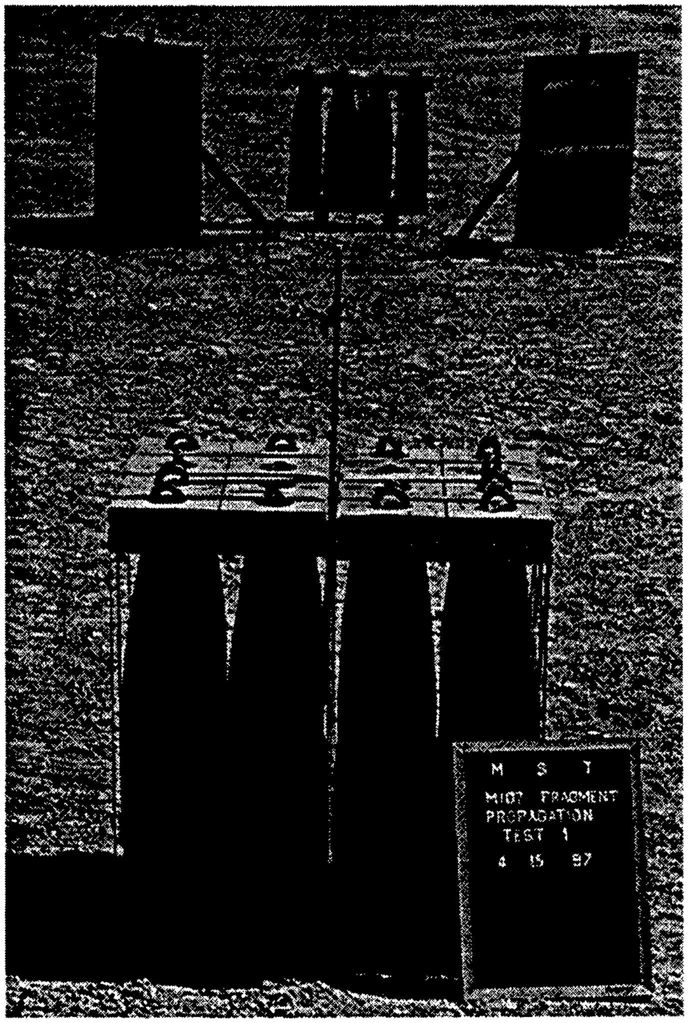


Figure 4. View of the Donor, East Acceptor, and Barricades in Test 1.

3.4 Fragment Propagation Experimental Results. In the first test, with the acceptor pallets placed 39 ft (skin to skin) from the donor (corresponding to a 50% predicted probability of detonation propagation), the east, south, and west acceptors were knocked over and the pallets were broken apart but the projectiles did not react, as shown in Figure 5. As shown in Figure 6, most of the projectiles in the four projectile rows facing the donor stack exhibited fragment impact marks, and one projectile from the east acceptor pallet had a penetrating impact into the explosive, but no reaction ensued. The north acceptor pallet reacted violently. All of its projectiles exploded, but all of their base plates were recovered, and the recovered fragments

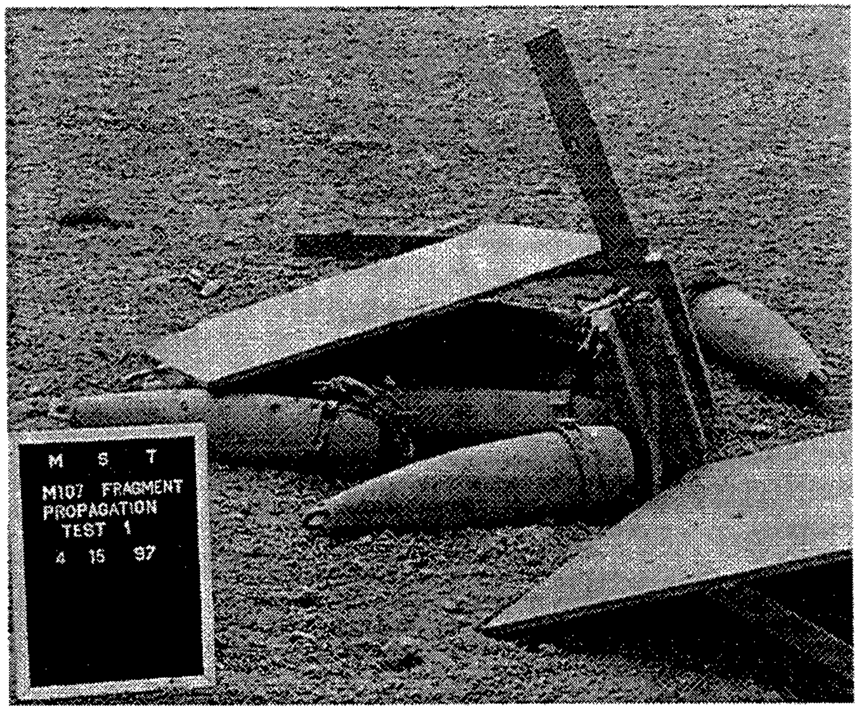


Figure 5. View of the South Acceptors After Donor Detonation in Test 1.

Figure 6. Projectiles From the East Acceptor Stack in Test 1 Showing Impact Craters. Note the Penetrating Impact on the Top Projectile.

were generally larger than those recovered from the (detonated) donor crater, as shown in Figure 7. Large fragments were thrown as far as 1,200 ft from the initial location of the stack. The explosions left a small crater. These factors indicate that violent explosion rather than detonation took place. The possibility of lower order reactions with M107s had not been previously considered, and it was decided to place witness plates under the acceptors in subsequent tests to provide an indication of the order of reaction.

In the second test, in order to increase the probability of propagation, the acceptor pallets were placed closer to the donor (28 ft, corresponding to a 75% predicted probability of detonation propagation). Figure 8 shows the east acceptor, west acceptor, and donor prior to the test. In this case, the north and south acceptors detonated. The witness plate at the south acceptor, shown in Figure 9, indicates that the projectiles detonated with varying degrees of completeness. The east acceptor reacted violently but did not detonate. Its witness plate, shown in Figure 10, indicated that the middle two projectiles in the row facing the donor and the second projectile from the left in the back row reacted. The remaining projectiles were ejected to distances of 550, 800, 800, 980, and 1,200 ft from their initial location. The west acceptor did not react, and all eight projectiles were recovered nearby, as shown in Figure 11.

In the third test, the acceptor pallets were also placed 28 ft from the donor. Following donor detonation, the east acceptor pallet detonated, producing the large crater shown in Figure 12. One projectile in the north acceptor stack reacted violently, scattering the other seven projectiles around the range. These projectiles were thrown to 200, 360, 615, 630, and 900 ft, with two projectiles remaining within a 200-ft radius. One of the projectiles is shown in Figure 13. Two projectiles in the west acceptor reacted violently, throwing the other six projectiles out to distances of 220, 300, 340, 700, and 920 ft, with one projectile remaining within a 200-ft radius. The south acceptor pallet, shown in Figure 14, did not react but was blown over and broken apart.

In the second and third tests, three of eight acceptors (37.5%) detonated at a standoff corresponding to a predicted frequency of detonation propagation of 75%. Three of the

Figure 7. Large Fragments Recovered From the North Acceptor (Top) Compared With Smaller Fragments From the Donor Crater (Bottom) in Test 1.

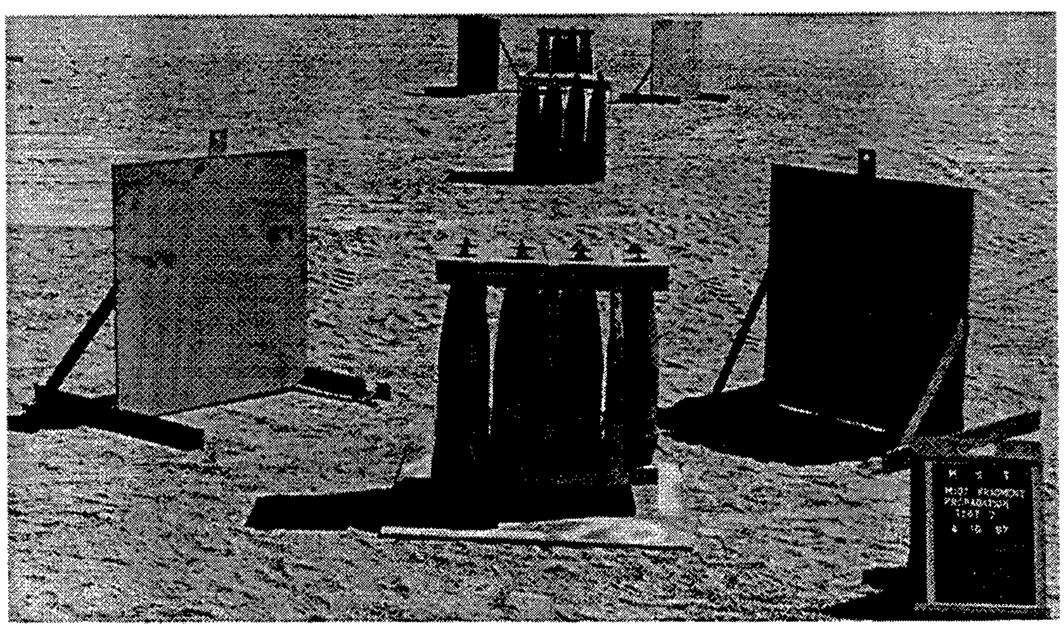


Figure 8. Arrangement for Test 2 Showing the Witness Plate at the West Acceptor.

Figure 9. The South Acceptor Witness Plate From Test 2 Showing Evidence of Detonation.

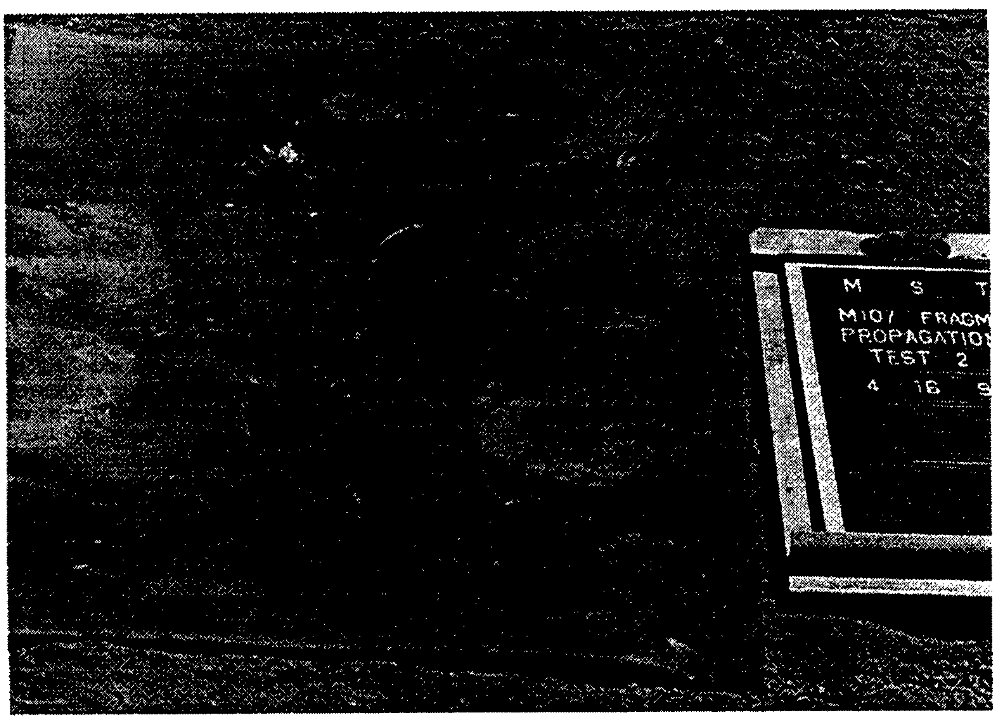


Figure 10. The Witness Plate From the East Acceptor in Test 2.

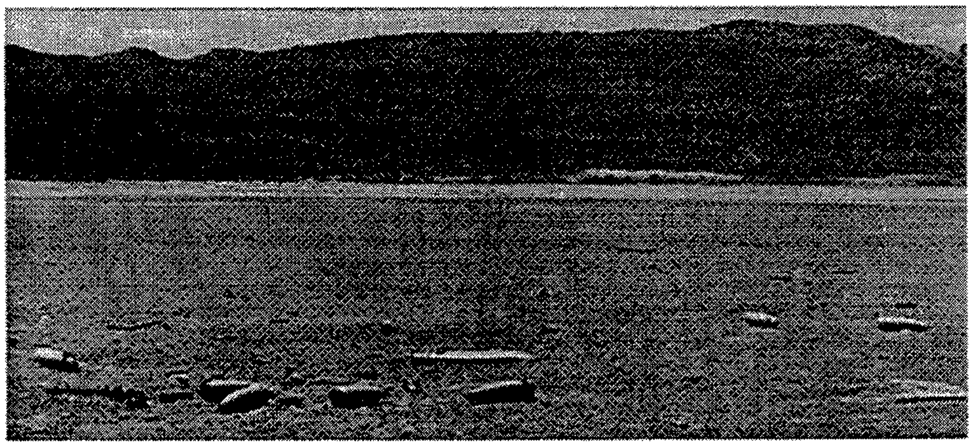


Figure 11. Scattered Projectiles From the West Acceptor in Test 2.

Figure 12. Crater From the East Acceptor Detonation in Test 3.

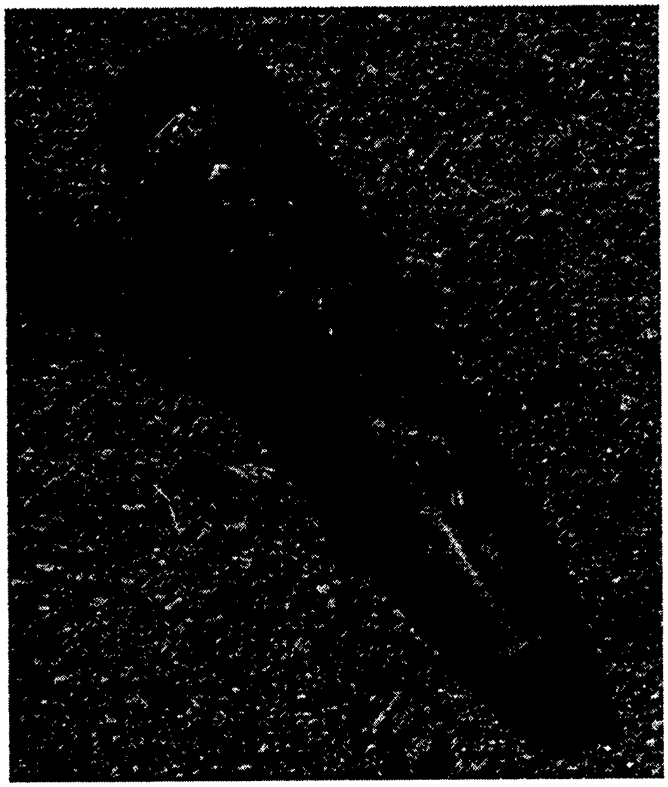


Figure 13. A Projectile From the North Acceptor Stack in Test 3 Was Ejected to 630 ft Along an Azimuth of 85°.

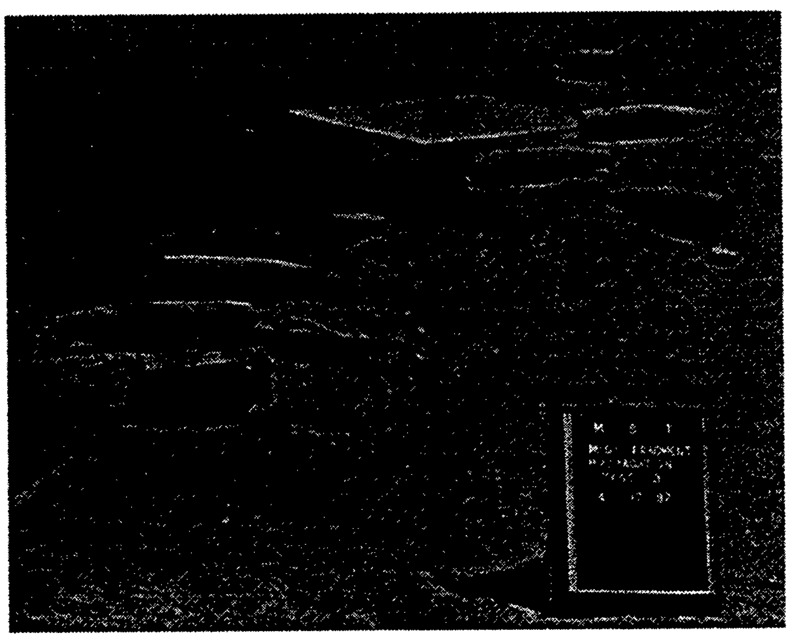


Figure 14. Scattered Projectiles From the South Acceptor Stack in Test 3.

remaining five acceptors (60%) reacted violently at a standoff corresponding to a predicted frequency of burning propagation of 80%. Thus, the predicted frequencies of detonation and burning propagation are somewhat greater than those observed in the tests.

4. Characterization of Fragments From Thin-Walled Warheads

4.1 Brief Review of FragGen. FragGen (Starkenberg, Benjamin, and Frey 1996) is a simple model for estimating the fragment output from any item that can be represented as a cylindrical charge with a fragmenting case. It does not account for fragment interactions with neighboring items. The distribution of fragment masses is given as a function of the average fragment mass by the Mott equation (Victor 1994). The average fragment mass may be related to the properties of the charge and casing, and the total fragment mass is equated to the casing mass. The velocity of the fragments is determined using the Gurney analysis for the assumed configuration and is the same for all fragments.

4.2 Choice of Ammunition. The first objective of the series of arena tests was to provide fragmentation data for a thin-walled shaped-charge missile warhead for comparison to a FragGen analysis. The AGM-114A Hellfire missile was chosen for availability. Its warhead has 14.1 lb of LX-14 in a thin aluminum case, and its motor has 20.5 lb of nondetonable propellant. It is classified in hazard division 1.1E for storage and shipping. In order to maximize the applicability of the FragGen analysis, the first arena test was performed on a single Hellfire missile without its container. Since the missile is not generally stored this way, another arena test with two simultaneously detonated missiles in their containers was performed. Finally, in order to address the issue of how to treat in situ detonation of weapons carrying submunitions, a test with a pair of 155-mm M864 ICM projectiles was attempted. Each projectile contains 72 submunitions, containing a total of 4.81 lb of Composition A-5 and 2.6 lb of base-burn HTPB-AP rocket propellant. It is classified in hazard division 1.1D for storage and shipping. The submunitions in the projectiles used in these tests were unfuzed.

4.3 Arena Test Arrangement. The arena configuration for the Hellfire missile tests is illustrated schematically in Figure 15, and a photograph is shown in Figure 16. In the first test, the Hellfire missile (without its container) was laid horizontally on a wooden stand with the centerline of the missile 4 ft above the ground. Bundles of Cellotex (4 ft wide × 8 ft high × 2 ft deep), numbered from 1 to 12 in a clockwise direction, were set 30 ft from the center of the missile at azimuthal stations 10, 20, 30, 40, 50, 70, 80, 90, 110, 120, 140, and 150° from the nose of the missile. The front surfaces of the bundles were covered with thick aluminum foil to produce visible flashes for measurement of fragment impact times. The 30-ft distance was chosen as sufficient to prevent blowover of the Cellotex panels based on the total explosive weight in two missiles. Three propellant witness panels (designated A, B, and C) were set at 60, 100, and 130° from the nose of the missile, at a slightly greater distance than the Cellotex panels. These consisted of steel plates on which six M203A1 metal canisters for the 155-mm howitzer were mounted and are shown in Figure 17. Each canister contains 30 lb of M31A1E1 stick propellant in a combustible cartridge case. They are classified in hazard division 1.3C for storage and shipping. A 24-in-high plywood fence was set up 16 ft from the missile. This served to prevent fragments ricocheting from the ground from hitting the panels without intercepting direct hits. The Hellfire missile was detonated by firing a bare Viper shaped charge through the center of its warhead, as shown in Figure 18. Two high-speed cameras, one viewing the left half of the arena and one viewing the right half, were placed 400 ft from the missile and recorded the tests at a nominal speed of 6,000 frames per second.

The second test, with two Hellfires, was arranged similarly to the first test. The two missiles, in containers, were positioned horizontally on a wooden stand, one above the other, with the centerline between them 4 ft above the ground. Because of the increased vertical distribution of fragment sources, the ricochet fence was moved out 6 in and its height decreased to 20 in. The missiles were detonated simultaneously using two bare Viper shaped charges placed symmetrically, one above the top missile warhead and the other beneath the bottom missile warhead. The arrangement is shown in Figure 19.

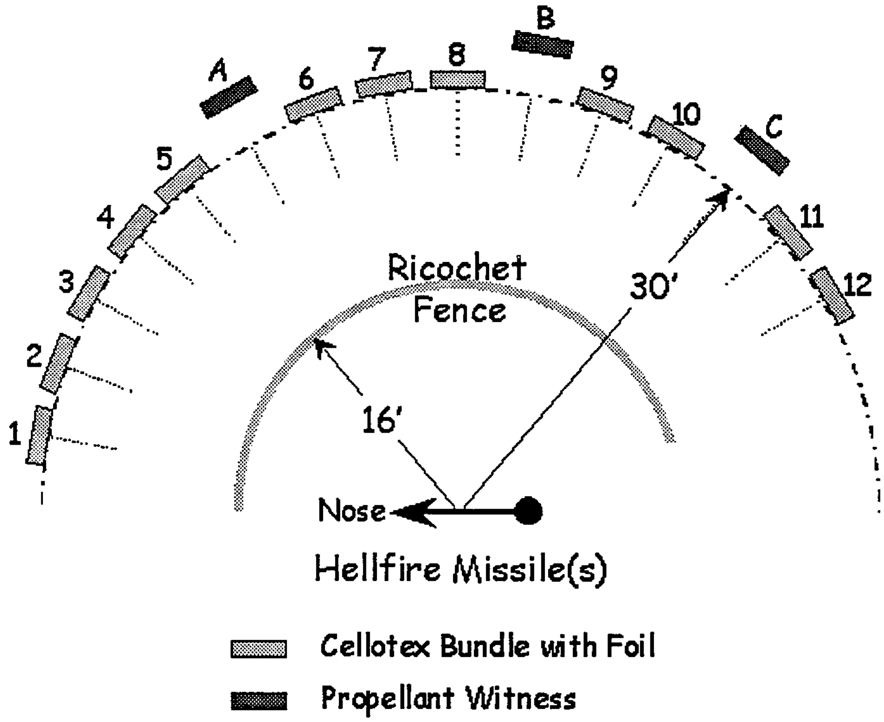


Figure 15. Schematic of the Hellfire-Missile Arena Tests.

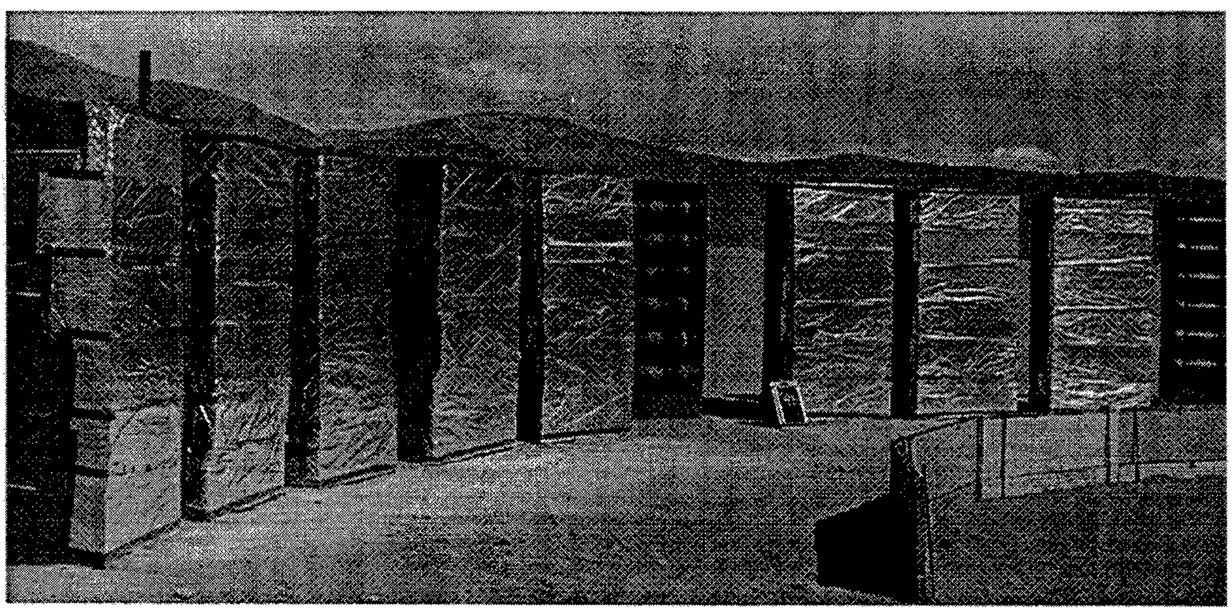


Figure 16. The Hellfire Missile Arena Test Arrangement Showing the Foil-Covered Cellotex Bundles, Propellant-Canister Witness Panels, and the Ricochet Fence.

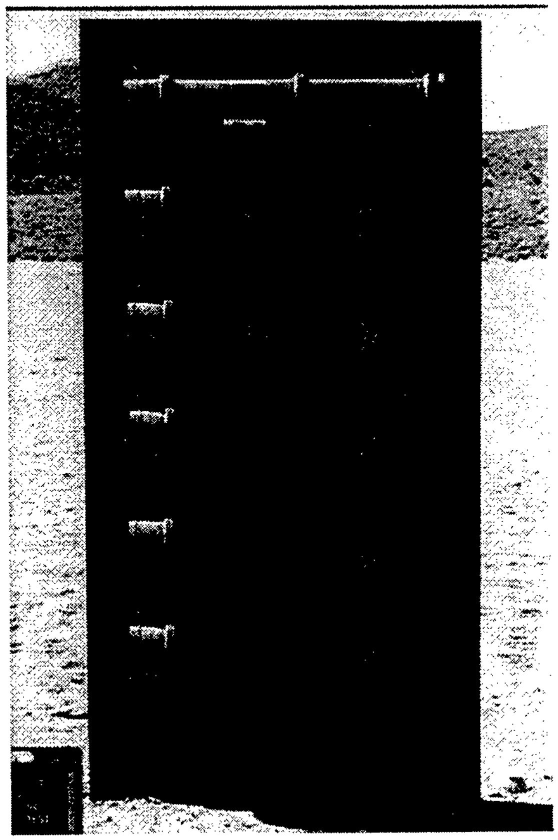


Figure 17. View of a Propellant-Canister Witness Panel.

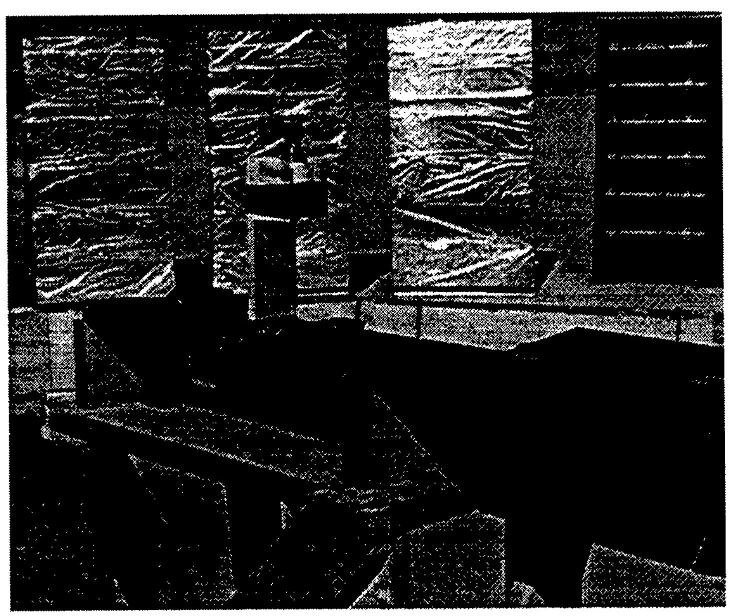


Figure 18. The Single Hellfire Missile With the Viper Shaped Charge in Place.

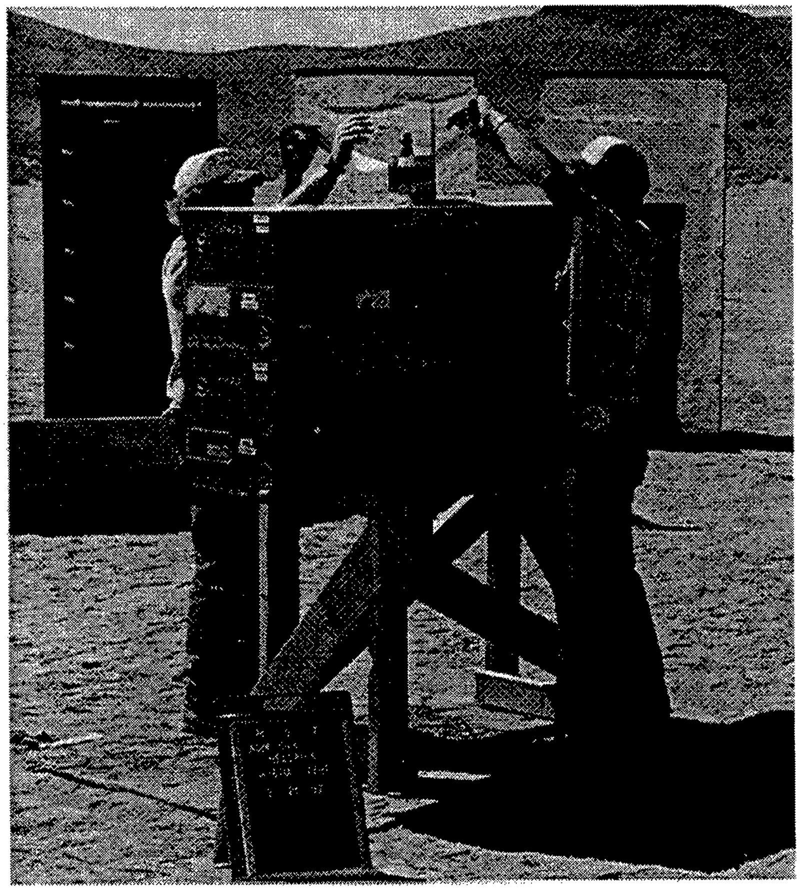


Figure 19. Two Hellfires in Containers. The Top Viper Shaped Charge Is Being Put in Place.

The arena configuration for the M864 projectile test was similar and is illustrated in Figure 20. Two projectiles were positioned horizontally on a wooden stand, one above the other, with the centerline between them 4 ft above the ground, as shown in Figure 21. Only six Cellotex bundles (numbered from 1 to 6) at azimuthal stations 20, 40, 60, 80, 100, and 120° from the noses of the projectiles were used. These were placed 23 ft from the projectiles. The three propellant panels were placed 3 ft further away at the 30, 70, and 90° azimuthal stations. These items could be placed closer to the M864s than to the Hellfires because of the lower explosive weight. A 21-in-high ricochet fence was placed 13.5 ft from the projectiles. The projectiles were primed in their expelling charge cavities with Composition C-4. This was detonated with a Reynolds exploding bridgewire detonator (RP-83) through two 18-in lengths of detonating cord.

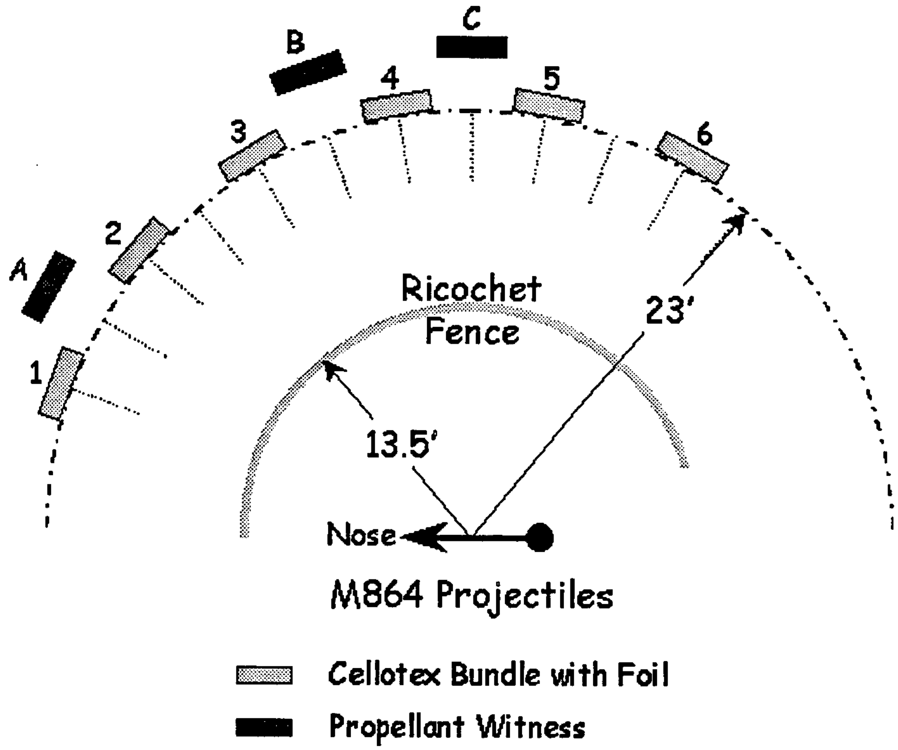


Figure 20. Schematic of the M864 Arena Test.

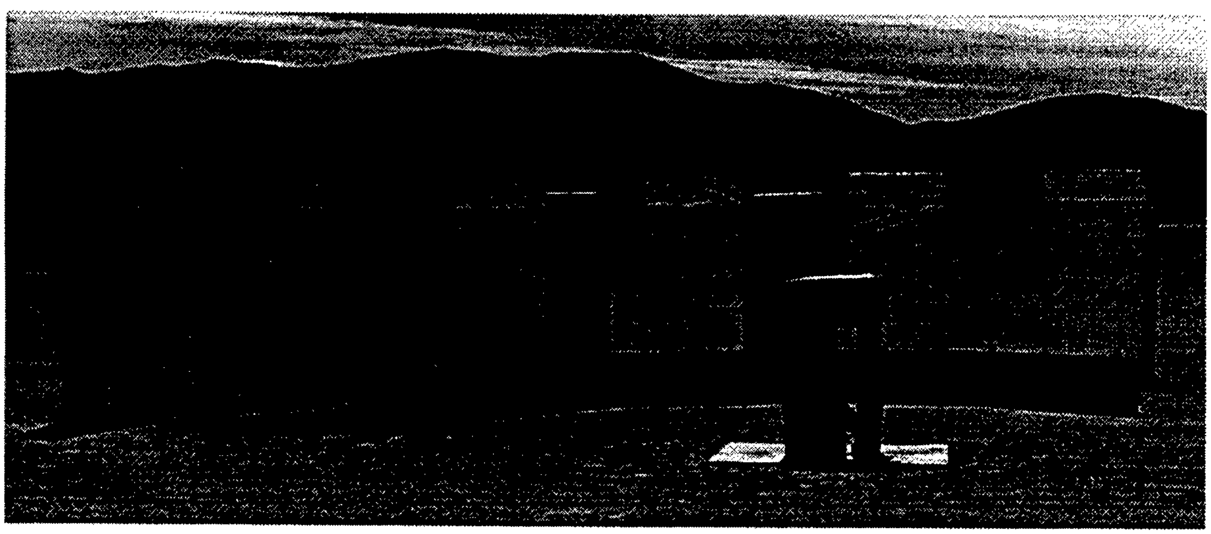


Figure 21. M864 Arena Test Arrangement.

4.4 Results and Analyses. The aftermath of the single-Hellfire arena test is shown in Figure 22. Many of the propellant canisters were dislodged from the witness panel, but none of them reacted and there were no penetrating impacts on any of them. The detonating warhead broke up the missile and ejected the motor 37 ft to the rear. The motor did not react and remained intact with no rocket propellant exposed. It is shown in Figure 23. The high-speed films were examined and found to have 6,170 frames per second. The only position not obscured by the fireball from the warhead detonation was at 150°, where flashes on the aluminum foil from fragment impacts were noted on the film and velocities were determined to range from 320 to 1,568 m/s. The fragments collected from the Cellotex bundles were identified as aluminum, copper, or steel and weighed.

Figure 22. A View of the Arena After the Single-Hellfire Test.

Distributions with azimuthal zone of the number of fragments and their total and average masses are shown in Figure 24. The aluminum fragments are generally small and distributed throughout the arena. Most of them are primary fragments from the warhead casing, although several larger aluminum pieces were retrieved from the Cellotex bundle at 150°. Fragments larger than 3 g were found in only a few of the azimuthal zones. The copper fragments are larger and are concentrated in the 30–50° azimuthal range. The steel fragments are also larger and distributed mostly toward the forward and aft azimuthal zones. FragGen predictions for an

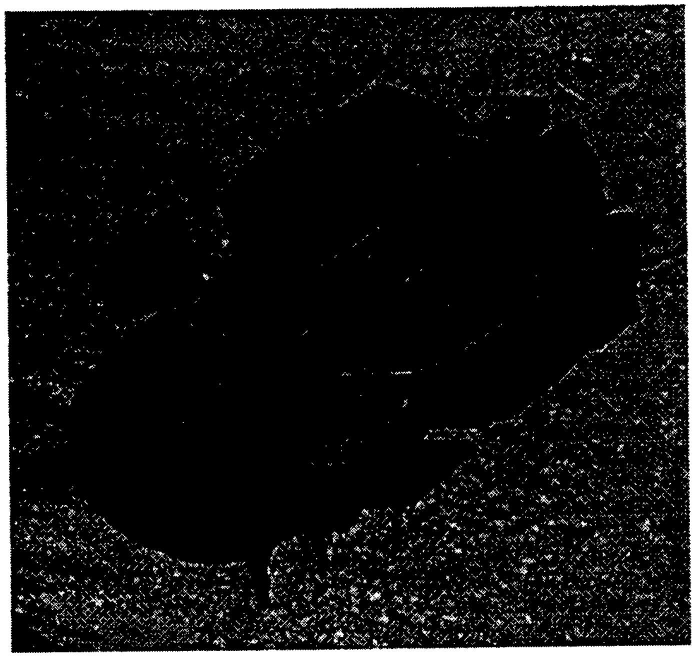


Figure 23. Rocket Motor Ejected During the Single-Hellfire Arena Test.

idealized representation of the Hellfire warhead were made. The assumption of a cylindrical LX-14 charge, 246 mm in length by 175 mm in diameter, with a 1.27-mm-thick aluminum case, gives a total of 1,878 fragments with an average mass of 0.247 g and a velocity of 3,896 m/s. Assuming a uniform distribution about the missile axis, only about 64 of these fragments would be expected to strike the Cellotex bundles. Actually, 238 aluminum fragments with an average mass of 0.85 g were recovered. These do not all come from the warhead casing. The larger fragments are probably secondary fragments from other parts of the missile. However, even if attention is restricted to fragments smaller than 1 g, there are still 202 fragments with an average mass of 0.22 g. Even though this average mass is close to the predicted value, there are still more fragments than predicted.

Histograms of the aluminum fragment mass distributions were prepared for comparison with predictions obtained from the Mott equation. Two different mass increments (0.1 and 0.02 g) were used. Histograms for all fragments below 3 g (comprising 96% of the total number of fragments) are shown in Figure 25. With 0.1-g increments, the comparison with the Mott prediction appears quite favorable to about 0.3 g (72% of the total number of fragments). From

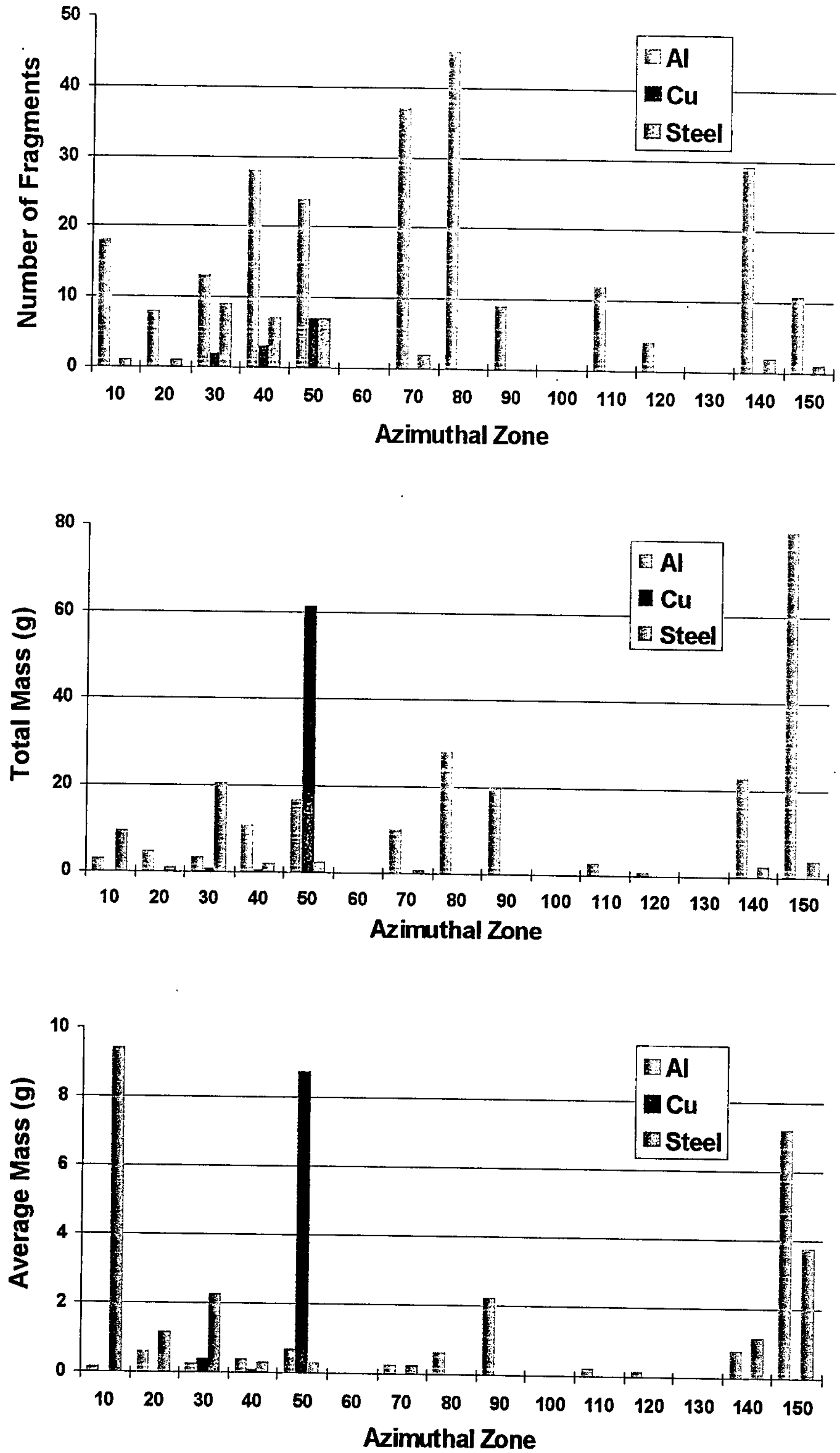
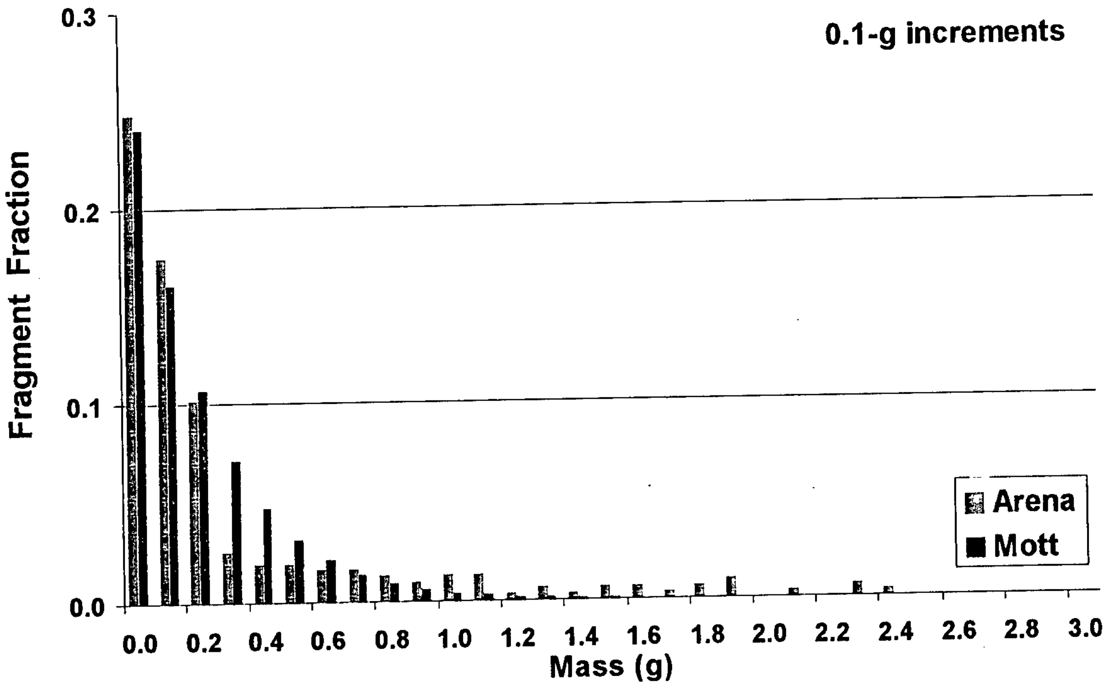


Figure 24. Distributions With Azimuth of the Number of Fragments, the Total Fragment Mass, and the Average Fragment Mass - Single Hellfire.



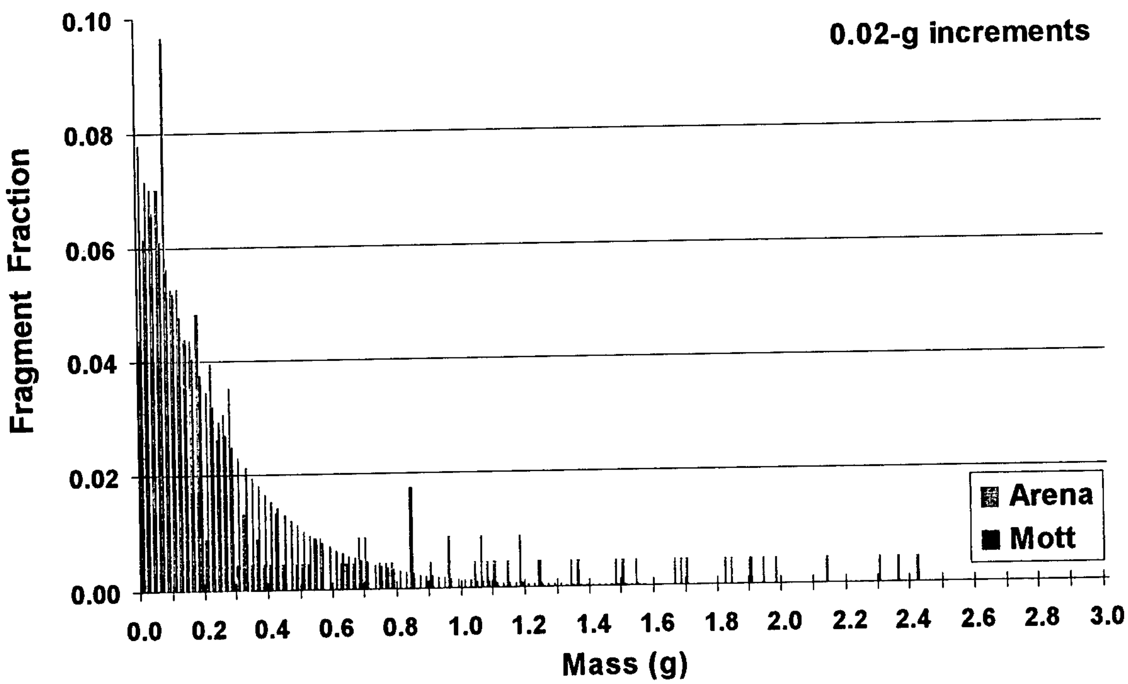
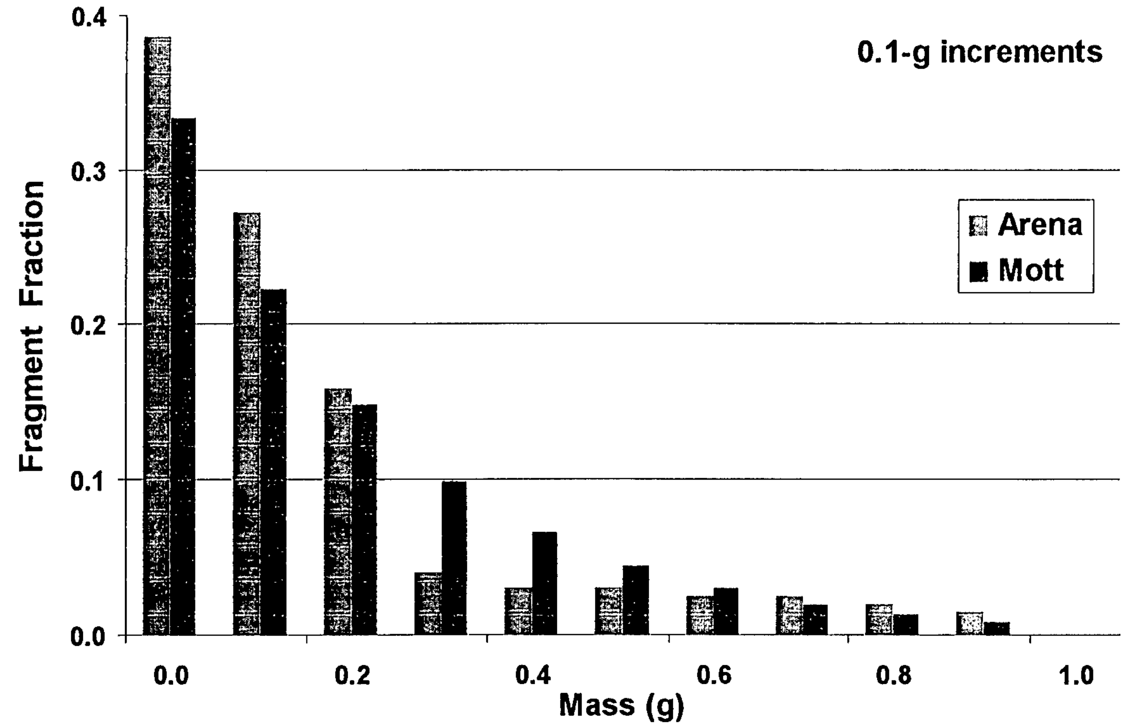


Figure 25. Distributions of Fragment Mass for Fragments Smaller Than 3 g - Single Hellfire.

0.3 to 0.6 g (11% of the fragments), there are fewer fragments than predicted, while above 0.6 g (17% of the fragments), there are more fragments than predicted. Using a 0.02-g mass increment, the histogram shows greater detail. While the Mott distribution is monotonic, the experimental distribution exhibits declining populations below 0.08 g. Thus, the Mott prediction is adequate only between about 0.10 g and 0.30 g (38% of the fragments). Because the primary fragments from the warhead case are expected to be smaller, the analysis was redone for fragments smaller than 1 g (84% of the fragments). The results, given in Figure 26 show no improvement over the 3-g sample.

In the second arena test, the simultaneous detonation of the two missile warheads produced a large blast wave and heavy fragmentation. The aftermath of the test is shown in Figure 27. There was an immediate reaction in a propellant canister in witness panel C, spreading burning propellant over a 50-ft radius. After approximately five minutes, the Cellotex bundles ignited and started burning. Upon reentering the range, all of the Cellotex was found to have burned. All of the propellant canisters had burned out, and some were thrown as far as 400 ft from their initial locations. Three canisters in witness panel C had penetrating fragment holes where the fire may have started. One of these is shown in Figure 28. Large amounts of unburned propellant were scattered around the entire arena area and scorch marks on the ground indicated that much propellant had been ignited and burned after being ejected from the canisters, as shown in Figure 29. One of the missile motors had been ejected intact 31 ft to the rear. The other ignited and was observed to fly upward approximately 300 ft, landing 600 ft from its initial position along an azimuth of 210°. Because of the large fireball from the two simultaneous missile detonations, flashes on the aluminum foil from fragment impacts could not be seen in the film and velocities could not be estimated. The fragments collected from the Cellotex ashes included missile and container parts. They were weighed and identified as aluminum, copper, or steel.

Distributions with azimuthal zone of the number of fragments and their total and average masses are shown in Figure 30. The aluminum fragments include primary fragments from the warhead casing and secondary fragments from the container. There is a greater percentage of large (greater than 3 g) fragments than produced by the single Hellfire detonation, and both large



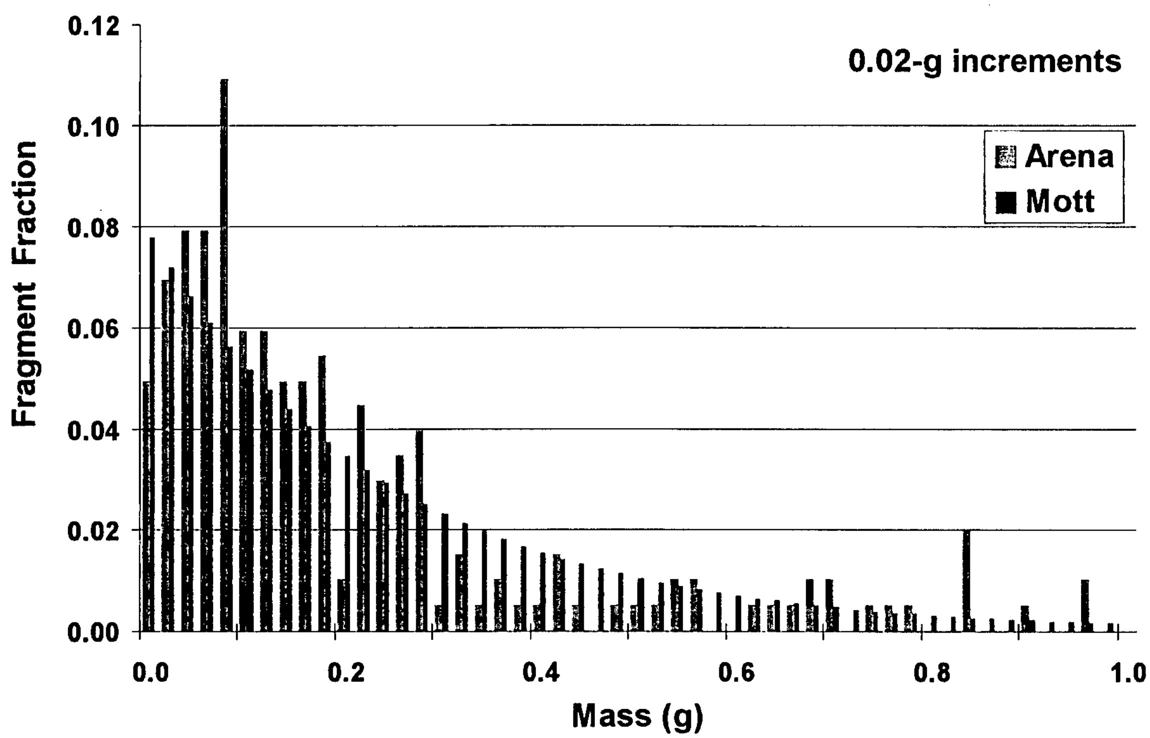


Figure 26. Distributions of Fragment Mass for Fragments Smaller Than 1 g - Single Hellfire.

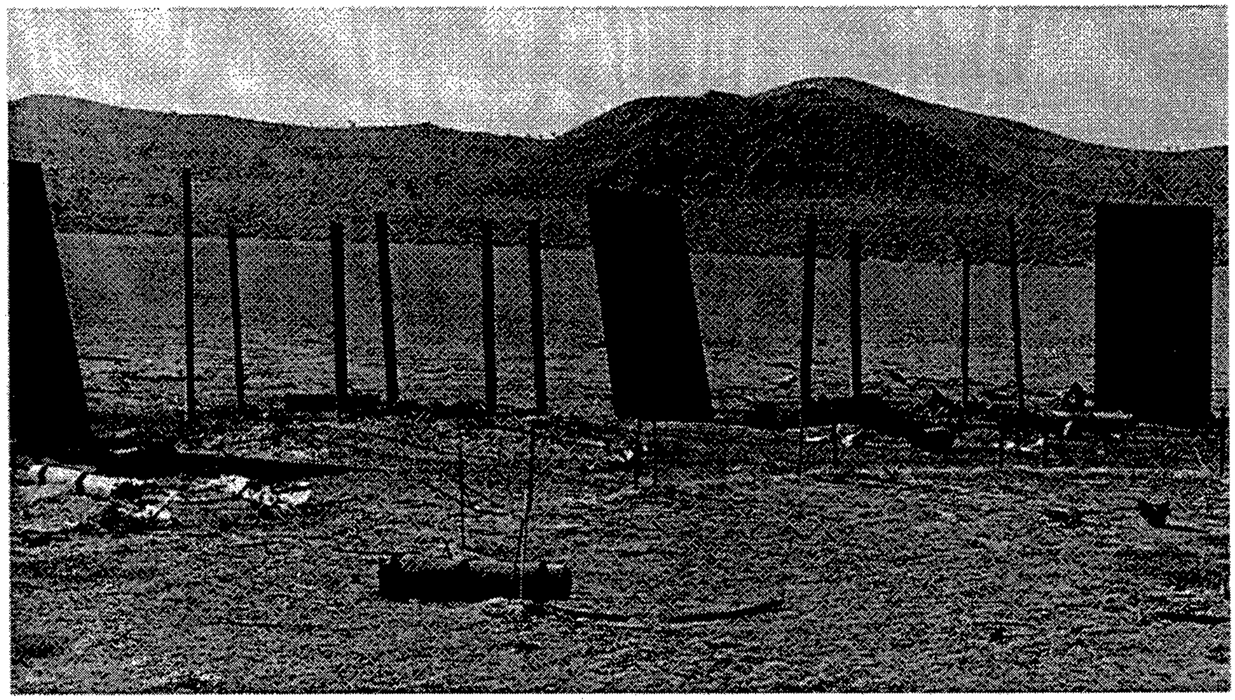


Figure 27. A View of the Arena After the Boxed-Hellfire Test.

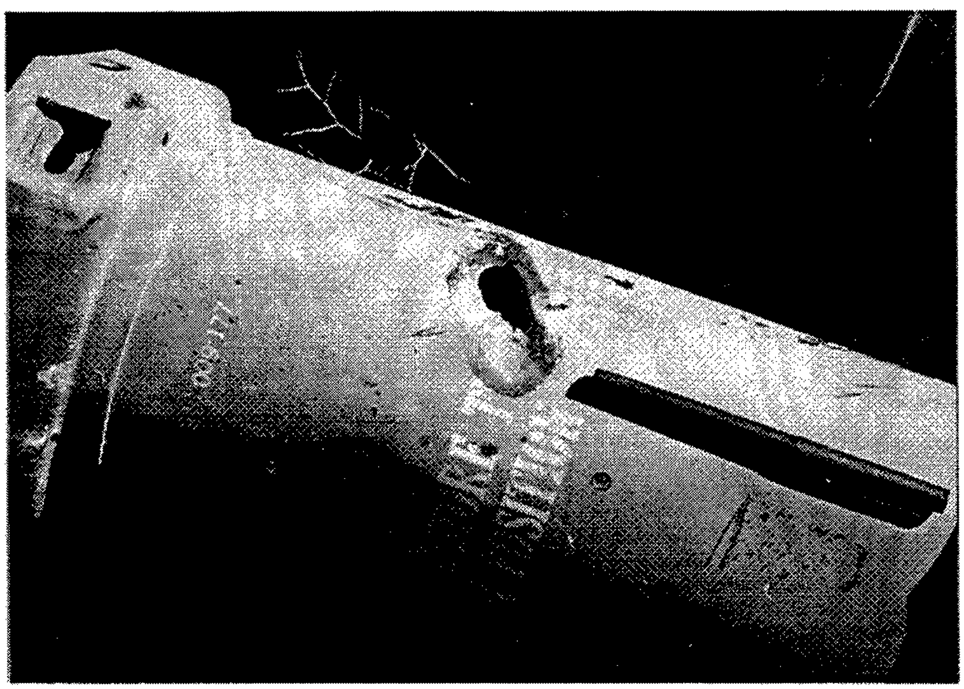


Figure 28. A Propellant Canister From the Boxed-Hellfire Arena Test Showing a Penetrating Impact.

Figure 29. Scorch Marks From Scattered and Burned Stick Propellant. Unburned Propellant Is Visible at the Top of the Picture.

and small fragments are distributed throughout the arena. Large copper fragments were recovered from the 40° azimuthal zone, and numerous small copper fragments were found at 80, 140, and 150°. Large steel fragments were also recovered from the 40° azimuthal zone, and smaller steel fragments were distributed throughout the arena, with numerous small fragments at 110°.

The distribution of fragment masses is compared to that from the single hellfire test in Figures 31 and 32. In the boxed Hellfire test, the smallest fragments appear more infrequently, while somewhat larger fragments appear more frequently. The smallest fragments may have been scrubbed by the container or consumed in the Cellotex fire.

In the third arena test, the two M864 projectiles appeared to detonate simultaneously and it was noted that several large fragments were launched. There was an immediate reaction from

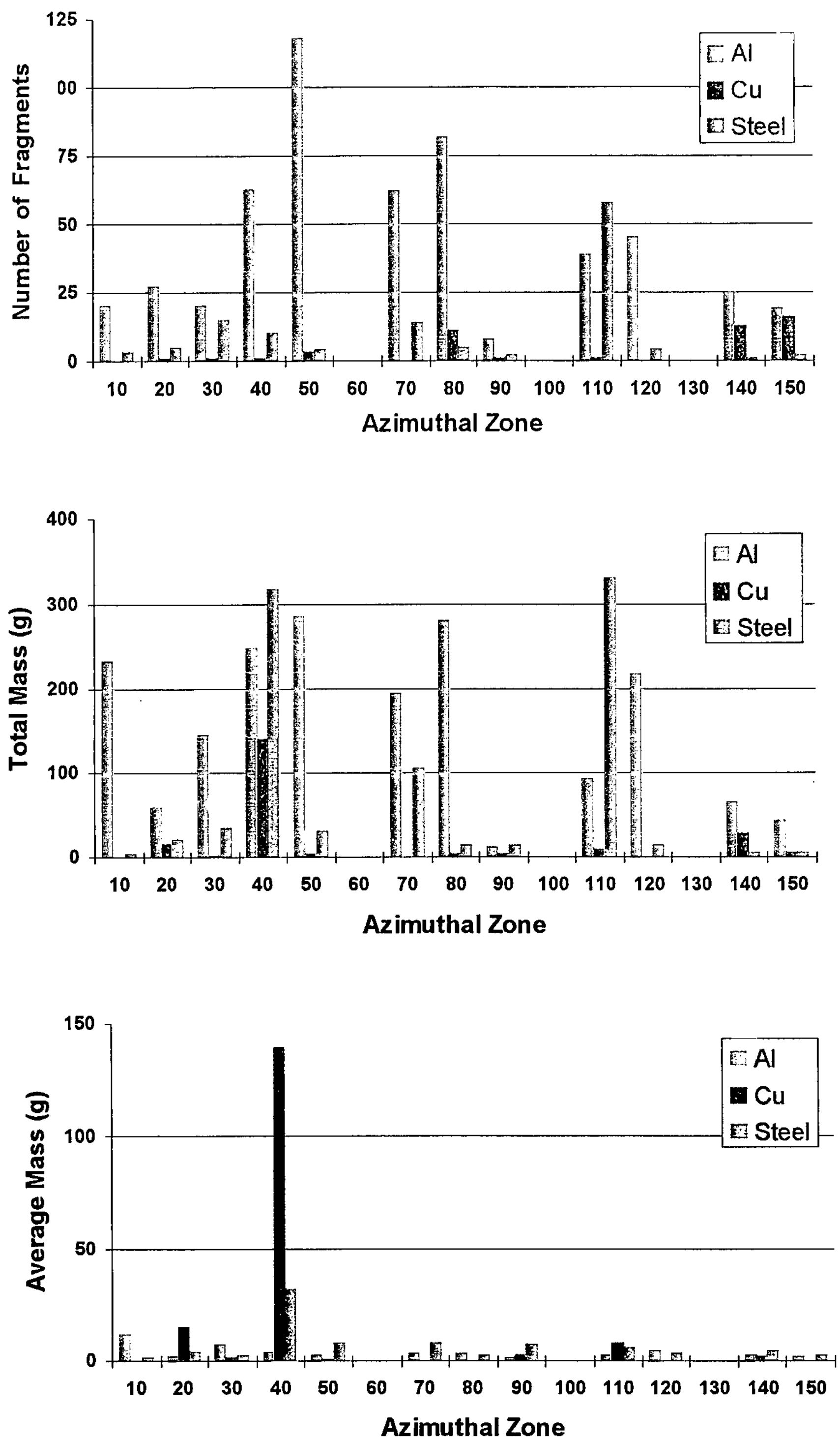


Figure 30. Distributions With Azimuth of the Number of Fragments, the Total Fragment Mass, and the Average Fragment Mass - Boxed Hellfires.

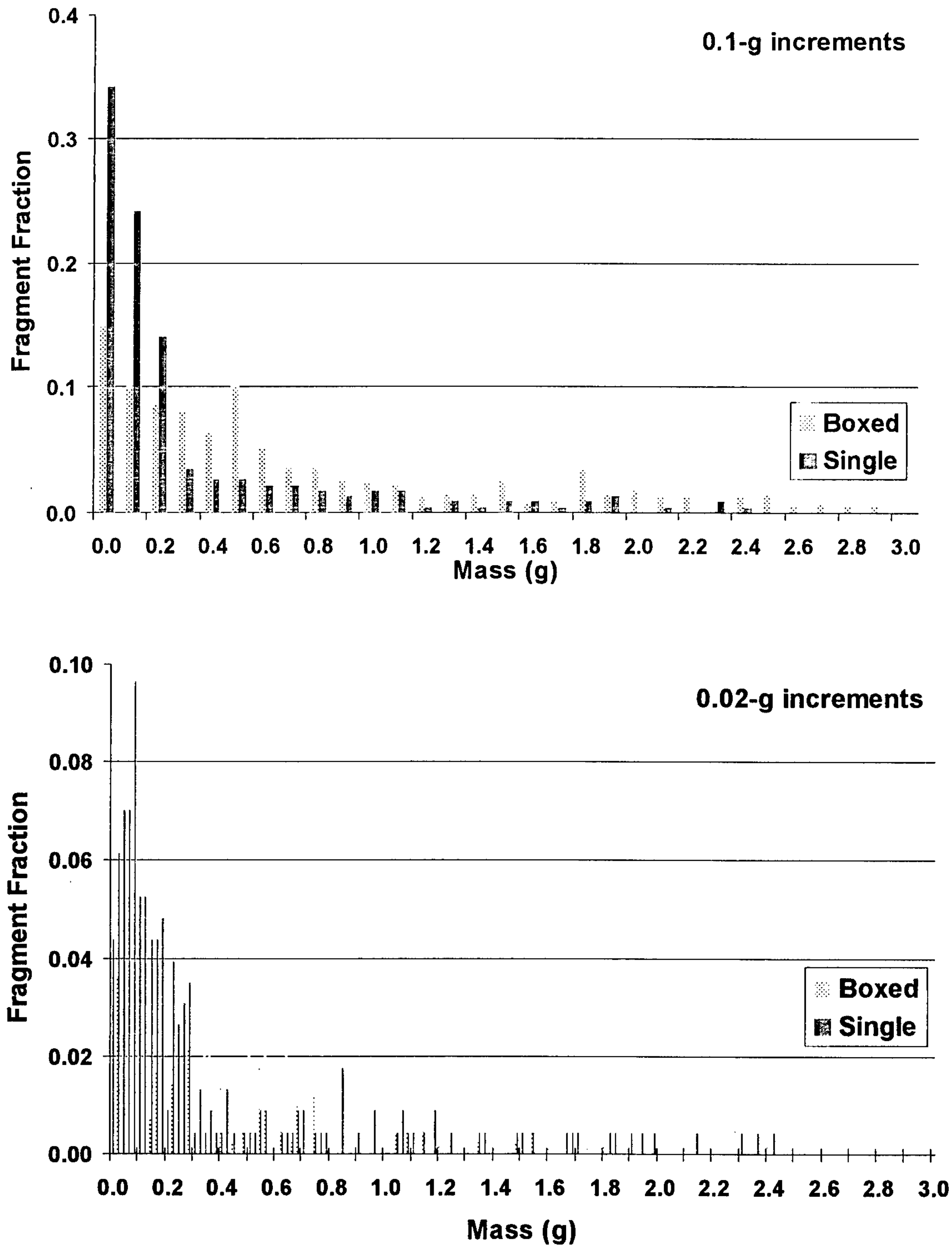


Figure 31. Distributions of Fragment Mass for Fragments Smaller Than 3 g Comparison of Single Hellfire With Boxed Hellfires.

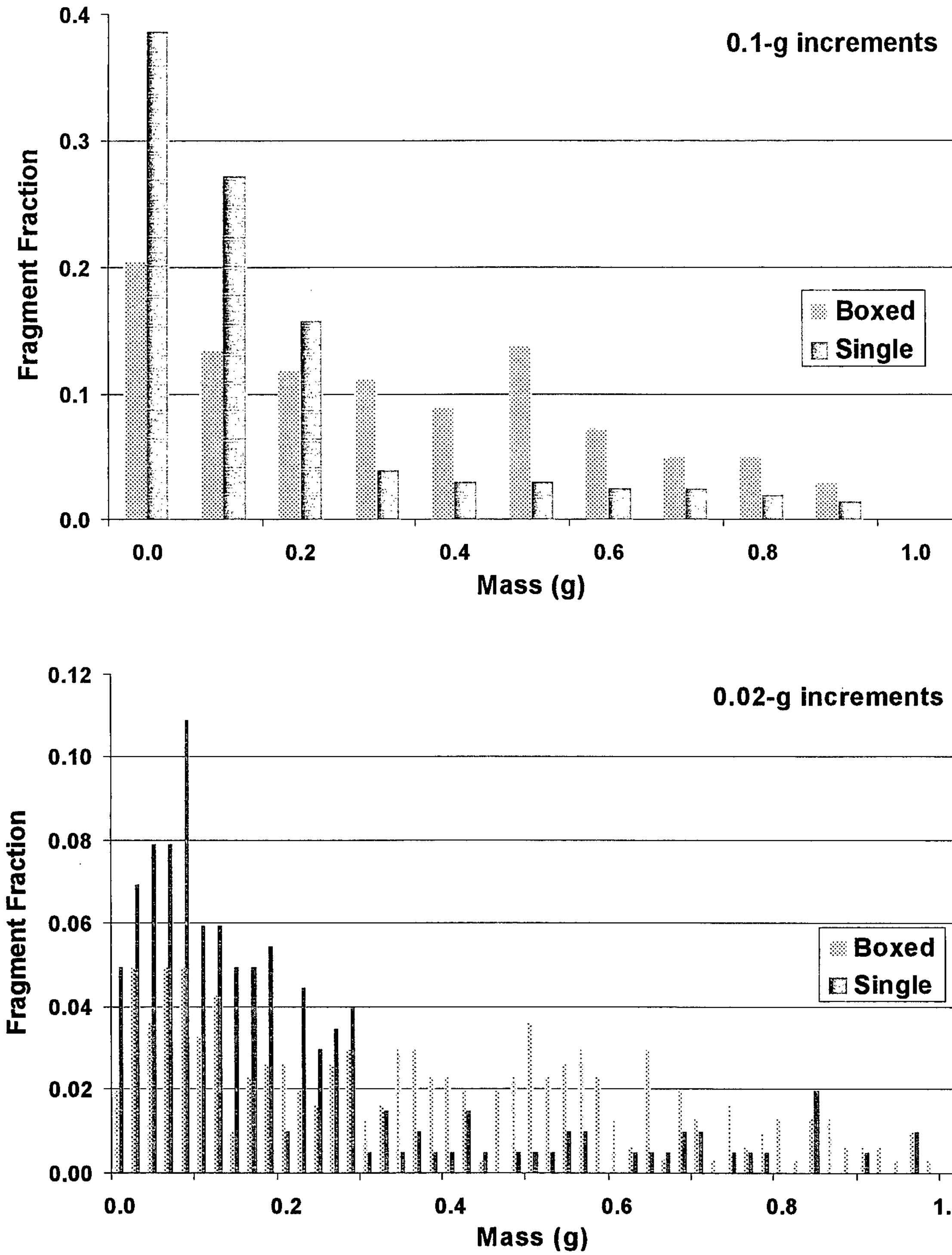


Figure 32. Distributions of Fragment Mass for Fragments Smaller Than 1 g Comparison of Single Hellfire With Boxed Hellfires.

the propellant canisters on witness panel C. Canister lids were ejected, and burning propellant was distributed. About 30 s after the initial blast, three explosions that are assumed to come from submunitions cooking off in the propellant fires were heard. Propellant from witness panel C continued to burn over the entire arena for about two minutes, igniting many of the Cellotex bundles. Upon reentry, it was found that all of the Cellotex bundles had again burned to the ground (see Figure 33), even though the witness panels had been moved back. There was evidence of burned and unburned propellant. Only three propellant canisters remained within the arena, while the remaining 15 canisters were thrown clear. These were scattered within a 250-ft radius. Twelve of the 144 submunitions were recovered nearly intact around the arena area. These are shown in Figure 34. Projectile body fragments were scattered between 4 and 358 ft from the initial position. These were generally very large (about 3 in × 12 in). Some of them are shown in Figure 35. These factors indicate that most of the explosive did not detonate. Because of this, no analysis was conducted.

Figure 33. A View of the Arena After the M864 Test.

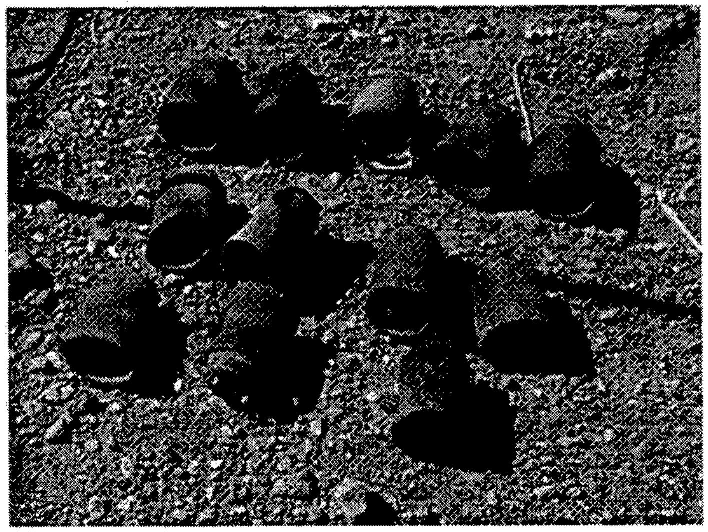


Figure 34. Recovered M864 Submunitions.

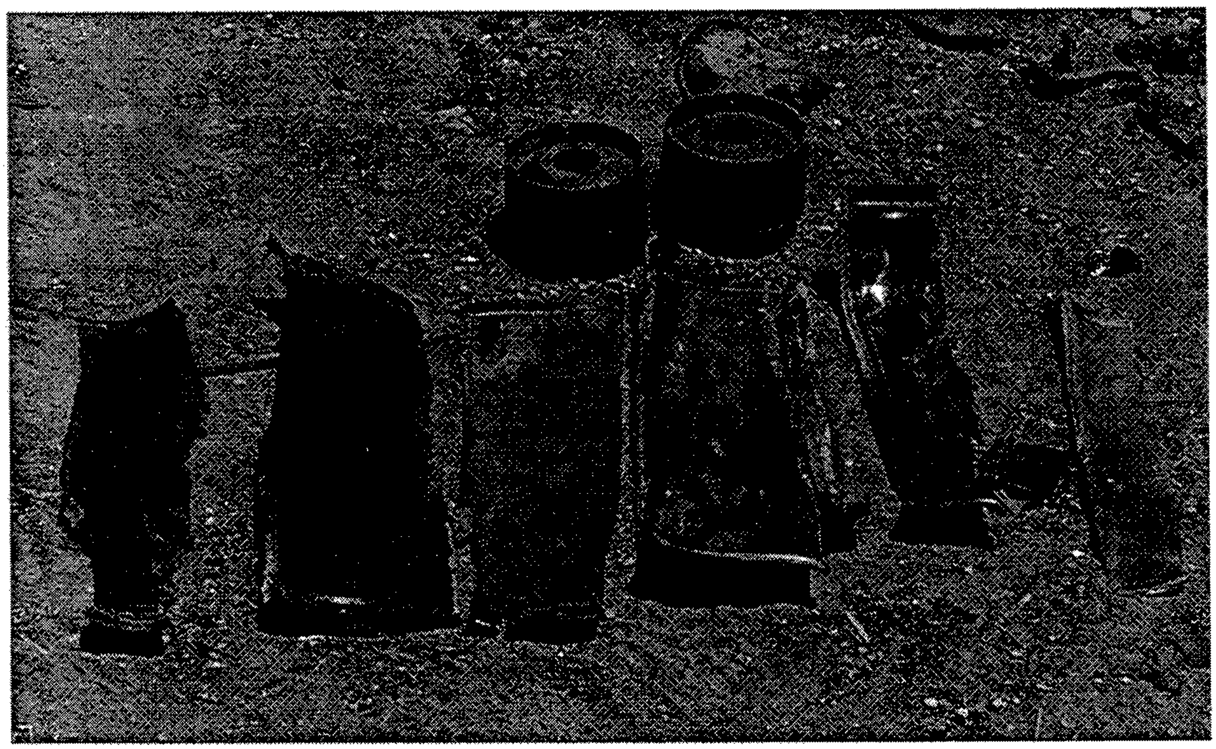


Figure 35. Recovered M864 Projectile Body Fragments. Intact Rocket-Assist Modules (Without Propellant) Are Visible at the Top

5. Summary and Conclusions

In order to benchmark predictions from FragProp, propagation tests using 155-mm M107 ammunition were conducted. The predicted frequencies of detonation and burning propagation are somewhat greater than those observed in the tests. While the results do not provide sufficient data to validate the FragProp predictions with a high level of confidence, they indicate that they are reasonable representations of the actual responses of these munitions.

In order to benchmark predictions of fragmentation from a missile warhead generated by FragGen, an arena test on a single Hellfire missile was performed. Aluminum fragments, in addition to those produced by the warhead, were recovered and analyzed. The analysis indicates that the predicted distribution is accurate for the smallest fragments, which comprise most of the total number. Measured fragment velocities were much lower than the Gurney predictions employed by FragGen, and the fragments failed to ignite any of the witness propellant canisters.

Because the configuration used in the single Hellfire test does not represent the actual storage arrangement and in order to determine the effects of multiple simultaneous detonations and the presence of external packaging, an arena test on two Hellfire missiles in their containers was conducted. Under these conditions, the Hellfires pose a hazard to nearby propellant canisters, as evidenced by the reactions observed. Comparison of the fragment mass distributions produced in the two tests indicates depopulation of the smaller fragment sizes in the second test. This renders the FragGen predictions inaccurate. The fragments produced in this test started burning reactions in the witness propellant canisters.

A final arena test with two 155-mm M864 ICM projectiles containing submunitions, conducted in an attempt to develop fragmentation data for this configuration, was not successful.

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Two models were developed at the U.S. Army Research Laboratory to enhance predictive techniques for propagation between ammunition stacks. For a mass-detonating ammunition stack, the FragProp model predicts probabilities of reaction in the energetic components of neighboring stacks by means of primary fragments as a function of distance between the stacks. An adjunct model, FragGen, was developed to estimate primary fragments from thin-walled warheads and detonable rocket motors. In order to increase confidence in the predictions from these models, benchmark tests were conducted. These include propagation tests with pallets of 155-mm M107 projectiles and arena fragmentation tests with Hellfire missiles and 155-mm M864 ICM projectiles. The test results are analyzed and compared with predictions from the models.

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